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Ferromagnetic Resonance of He^3-Irradiated Thin Metal Films

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CONTENTS

ABSTRACT

Ferromagnetic-resonance measurements at 9.5 GHz were made on a number of films of pure iron and pure nickel, and alloys of iron and nickel (Permalloy) before and after 2-MeV He^3-particle irradiation. The film thicknesses varied from several hundred to several thousand angstroms. The He^3-particle flux was about $3\times10^{17}/cm^2$ and, during irradiation, the film temperature did not exceed 81°C, as determined by thin-film thermocouples. The resonance field as a function of angle in the film plane, $H_0(\theta)$, and the half-width, ΔH, were measured at room temperature. In general, H_0 decreased (by about 2 oe, 35 oe, and 15 oe for the iron, Permalloy, and nickel films, respectively) as a result of the irradiation, except for the composition range between 26 and 37 percent Ni, where H_0 increased. Also, the half-width generally decreased with irradiation, and the half-width change was smallest for compositions around 76 percent Ni. For the pure iron and nickel films, the changes in H_0 can be attributed to changes in the radially isotropic stress in the plane of the film, $\Delta\sigma$, and in the uniaxial anisotropic field, ΔH_k, assuming that the saturation magnetostrictive constant, λ, and magnetization, M_s do not change with irradiation. For the alloy films where irradiation-produced ordering may occur, M_s, as well as σ and H_k, may also change. The changes in H_0 were different for films of a given set evaporated onto various substrates (soft glass, fused quartz, single-crystal quartz, and copper). Irradiating films in a saturating magnetic field, in the remanent state and in the demagnetized state gave H_k's which were larger, the larger the magnetic induction of the film during irradiation. Irradiating a film (or reirradiating a previously irradiated film) in a magnetic field also rotated the easy axis of the film into the direction of the field applied during irradiation. The rotation of the easy axis was observed over the entire composition range from pure iron to pure nickel. For the pure iron and pure nickel films, the rotation can be explained only on the basis of alignment of defects in the film during irradiation. For the Permalloy films, a short-range directional ordering effect might also apply. The variation with composition of the values of H_k after irradiation agree qualitatively with the values obtained by others using static techniques.

PROBLEM STATUS

This is a final report on one phase of the problem; work on other phases of the problem is continuing.

AUTHORIZATION

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FERROMAGNETIC RESONANCE OF He^3-IRRADIATED THIN METAL FILMS

INTRODUCTION

Although ferromagnetic-resonance experiments have been widely used in the past on bulk as well as film samples (1), this technique has been used only recently to investigate neutron-irradiated bulk metals (2) and γ-irradiated Permalloy films (3). Biller (2) has irradiated bulk samples with 10^{18} neutrons/cm^2 and has found no change in the half-width of the resonance line of nickel, nickel with manganese (0.28 percent), and commercial nickel. He suggested that the reason for the negative result was that the scattering cross section of the isolated defects and clusters of defects formed by the irradiation is too small to interact with the spin waves in the sample. Another possibility is that the integrated irradiation flux was too short to create a large enough density of displacements. Van Itterbeck, et al. (3) irradiated Permalloy films with γ rays (1.17 MeV, 2500 r/hr for eight hours) and found that "the resonance absorption was apparently unchanged after irradiation." Their films were between 700 Å and 3600 Å thick and were evaporated at 10^{-8} and 10^{-9} torr onto glass or quartz substrates. Again their negative results may have been due to an insufficient density of displaced atoms.

On the other hand, torque-magnetometer and hysteresis-loop measurements made on irradiated thin films (4) show that the uniaxial anisotropy constant, K_u, generally increases and the coercive force, H_c, generally decreases as a result of irradiation with He^3 particles as well as with neutrons. The changes were attributed to either short-range ordering of Fe atom pairs or to defect alignment.

Several differences are noted in the effects of charged-particle irradiation on films as contrasted with bulk metals. First, the damage is uniform throughout the film, since the range of 2-MeV He^3 particles in nickel, for example, is around 50,000 Å.* Second, the damage may be expected to anneal out more rapidly in films than in bulk material, since the defects caused by the radiation can move to the surface of the film, where they are annihilated. Finally, maintaining low film temperatures during irradiation requires special techniques, since the film is generally placed on an insulating substrate.

In the present report a number of ferromagnetic-resonance experiments involving He^3-irradiated thin metal films will be discussed. After the experimental techniques are given, the results of the effects of different substrates, of the application of a magnetic field during irradiation, and of composition will be analyzed.

EXPERIMENTAL ARRANGEMENT

Ferromagnetic Resonance Measurements

A Varian EPR spectrometer with 400-cps field modulation was used for all the measurements. A klystron frequency of 9.518 GHz was locked onto the sample cavity frequency by means of an afc system. A cavity with a 1/8-in.-diameter hole in the bottom was designed to allow only a small portion of the film to be examined. The sample was placed up into the recessed region of the bottom plate by means of a sample

*From an unpublished communication entitled "Energy Loss and Range of Protons, Deuterons, Tritons, He^3, and Alphas in Carbon, Aluminum, and Nickel," Van de Graaff Branch, Nucleonics Division, Naval Research Laboratory, Aug. 1, 1963.

holder which permitted rotation of the film about an axis perpendicular to the plane of the film. The hole through the bottom plate was made small enough so that only a small amount of dispersion occurred at resonance, and yet large enough so that a macroscopic average of the resonance parameters over the central area of the film was obtained. There was very little dispersion, as shown by the fact that the klystron frequency shift was at most 0.05 percent as the resonance curve was swept out. The hole was also made large enough so that the nonuniformity of the microwave field at the sample was not excessive. To determine if this was the case, a small piece of film was placed on the end of a rod and the resonance field, H_0, and half-width, ΔH, were measured at various locations of the sample as it was moved up into the cavity. The resonance field and the half-width changed slightly as this procedure was carried out, but no significant changes were observed. Since the sample was located at the same position relative to the hole in the bottom plate for the before- and after-irradiation measurements, and since only changes brought about by irradiation are of interest, the effect of small nonuniformities in the microwave field were unimportant.

All measurements were taken with the dc magnetic field in the plane of the film. The resonance line half-width was taken as the width of the line between the extrema of the derivative of the absorption-versus-field curve.

The dc field was produced by a Varian 12-in. electromagnet and regulated magnet power supply, and the magnetic field was measured with a Numar M-2 nuclear gaussmeter, a wideband preamplifier, and an electronic counter. A 10-pf capacitor was inserted into the M-2 oscillator to couple the oscillator to the counter via a preamplifier. The klystron frequency was obtained by connecting the 20-db coupler of the microwave bridge to a transfer oscillator whose output fed another electronic counter. The reproducibility of the H_0 and ΔH measurements was between ±0.10 to 0.20 oe, and ±0.5 to 1.0 oe, respectively, except for the low-intensity, broad nickel film lines, where the reproducibility was not as good (±1 oe for H_0 and ±2 to 4 oe for ΔH).

Thin Films

All films were evaporated in a vacuum system which had a pressure of 4×10^{-7} torr before evaporation and 1 to 5×10^{-5} torr during evaporation. The bell jar contained a coil of copper tubing (total surface area 600 in.^{2}) through which liquid nitrogen was circulated just prior to and during evaporation. This arrangement also helped to maintain low pressures during evaporation. The substrates, substrate holder, evaporant, and evaporant holder were all outgassed before the evaporation, which lasted generally around three or four minutes.

The following types of substrates were used: fused quartz (from Amersil Quartz Co.) with a density of 2.21 g/cm^3, soft glass (ordinary microscope cover slides) with a density of 2.47 g/cm^3, single-crystal quartz with a density of 2.60 g/cm^3, and copper with a purity of 99.999 percent. All silica substrates were cleaned in the following way: washed with tap water and detergent; rinsed in distilled water; heated in a solution of KOH and alcohol; boiled in distilled water; wiped dry with Kim wipe; mounted in substrate holder; dust removed just prior to insertion into vacuum chamber by an electrostatically charged brush.

The evaporants consisted of iron, nickel, and alloys of iron and nickel. The specified purity for both the iron and nickel, as received from the manufacturer, was 99.999 percent. The film was not necessarily the same composition as the evaporant, because of differences in evaporation rates of iron and nickel and because of different accommodation coefficients (5) of the substrate for the nickel and iron atoms. Therefore the composition of the films was determined by x-ray fluorescence, based on a wet-chemical-analysis calibration.

The quality of the films was generally good. Most of the films contained a large number of very tiny pinholes. The exact reason for this occurrence is not known, although it has been suggested (6) that high-energy macroscopic particles coming off the evaporant may be the cause. No attempt was made to correct for these pinholes, since their small size and relatively small volume, compared with the rest of the film, would probably cause little effect on the resonance field and half-width. Nevertheless, this point probably should be investigated further.

Irradiation

All irradiations were made at the end of the 16-degree beam port of the NRL Van de Graaff generator, with a 2-MeV He^3 particle beam current usually between 8 and 10 μamp. For an eight-hour irradiation this beam generally gave an integrated charge of 0.3 coul and a flux of 3×10^{17} He^3 particles/cm^2. A scanner was used to sweep the beam in a circular pattern of 1-1/8 to 1-1/4 in. diameter at the sample position, enabling four samples to be irradiated simultaneously. For the last irradiation, a new scanner was used which allows up to 16 samples to be irradiated at one time.

In the first two irradiations, the temperature was monitored with a nickel-copper thin-film thermocouple. This thin-film thermocouple was used in order to simulate the temperature excursions of the irradiated samples. The thermocouple was made by evaporating a layer of Cu and then a layer of Ni onto a substrate of the same type as used for the films under investigation. Each layer was around 1500 Å thick in order for the total thickness to be close to that of the films being studied. Prior to the irradiation, the thermocouple was calibrated at three different temperatures, and the thermoelectric power was found to agree with the bulk value of the thermoelectric power of copper versus nickel, 22 μV/degree (7). Some indirect checks indicated that the irradiation of the thermocouple thin film did not change its thermoelectric power. This result agrees with previous work (8a) on thermoelectric power studies of neutron-irradiated bulk thermocouples.

A simple calculation shows that, assuming no thermal losses, the temperature of the film and substrate will rise about 18°C/sec as a result of the dissipation of the beam energy in the substrate. In order to remove this heat it is necessary to make good thermal contact to the insulating substrate. An alloy consisting of 25 percent In-75 percent Ga, which is liquid above 15°C (9), was found to wet the quartz, soft glass, and metal substrates quite well and provided the necessary thermal contact. The liquid alloy was placed both on the back of the substrate and on the flange to which the substrates were attached; this flange was, in turn, placed on the end of the irradiation tube. The substrates were thus held to the irradiation holder simply by surface tension.

During irradiation, a stream of compressed air was directed at the back of the flange on the irradiation tube. After four hours, the temperature of the thin-film thermocouple rose to an equilibrium value of 56°C during the first irradiation and 81°C during the irradiation of the second set of films. Hence, the liquid-alloy contact between the substrate and the flange apparently was quite efficient in conducting the heat away from the film and substrate.

A magnetic field was applied to the films during selected irradiations by means of a variable-gap permanent magnet. With gaps of 3-3/4 and 6-1/2 in., the magnetic field at the sample positions was 425 and 168 oe, respectively.

Table 1
Summary of Data for a Number of Films

Sample	Composition (percent)	Substrate	Before/After Irradiation	H_e (oe)	H_h (oe)	Thickness (Å)	H_k (oe)	$\Delta\sigma$ (10^9 dyne/cm^2)
H"-5	100 Ni	s.g.	Before	1386.5	1389.5	6800	1.5	-0.4
			After	1371.2	1379.9		4.3	
S-1	89 Ni	c.q.	Before	954.4	1101.5	3000		
			After	979.8	1058.6			
S-5	89 Ni	s.g.	Before	1052.5	1055.0	3000	1.3	-2.9
			After	1034.8	1042.8		4.2	
S-9	89 Ni	f.q.	Before	1072.3	1075.1	3000	1.5	-4.3
			After	1048.1	1053.6		2.9	
Q-6	85 Ni	f.q.	Before	971.5	975.0	4000	1.8	
			After	951.5	961.3		5.1	
Q-9	85 Ni	f.q.	Before	976.1	981.2	4000	2.6	
			After	956.5	966.4		5.1	
			Before 2nd	956.1	966.7		5.5	
			After 2nd	955.9	966.3		5.4	
V-7	78 Ni	s.g.	Before	761.1	767.8	10,600	3.4	
			After	734.9	763.8		14.8	
V-9	78 Ni	Cu	Before	755	763	10,600	4	
			After	746	755		4	
H-6	75 Ni	f.q.	Before	824.1	843.8	3500	10.2	
			After	807.6	836.4		14.8	
L"-7	53 Ni	s.g.	Before	648.7	663.1	3300	7.2*	
			After	629.2	670.9		20.9*	
H'-1	50 Ni	s.g.	Before	669.3	681.4	1000	6.0*	
			After	641.4	681.2		19.9*	
X-4	37 Ni	s.g.	Before	623.7	638.8	7500	7.7	
			After	628.3	657.3		14.8	
X-9	37 Ni	Cu	Before	614	629	7500	8	
			After	618	634		8	
J-3	34 Ni	f.q.	Before	580.6	584.2	2700	1.8	
			After	583.6	593.8		5.1	
A"-7	26 Ni	s.g.	Before	476.7	501.6	4800	12.4*	
			After	479.3	506.2		13.5*	
O-1	Fe	f.q.	Before	574	581	680	3	
			After	573	578		2	
N'-2	Fe	s.g.	Before	519.9	521.8	540	0.9	-4.8
			After	517.5	520.9		1.7	

Substrate: s.g., soft glass; c.q., crystal quartz; f.q., fused quartz; Cu, copper.

*H_k is obtained from $(H_h - H_e)/2$ for these films.

CHANGES IN THE RESONANCE FIELD

The resonance field H_0 was measured as a function of angle θ in the plane of the film, while the half-width of the resonance line was usually measured with the dc field along either the easy or the hard axis. For some typical films, the results of these measurements, made before and after irradiation, are presented in Table 1. The data are presented in the form of values of the resonance fields H_e and H_h, measured with the dc field along either the easy or hard directions of magnetization, respectively. In general, it is seen that H_e and H_h decrease as a result of irradiation, with the decrease in H_e being greater than the decrease in H_h, although there are several exceptions. For the compositions between 26 Ni and 37 Ni,* H_e and H_h increased, with the increase in H_h being greater than that in H_e; for the 53 Ni film H_e decreased, but H_h increased; for the film on the crystal quartz substrate, H_e increased but H_h decreased. The variations in the half-width change with composition are given in Table 3, which appears in the section titled "Effect of Composition."

*Throughout this paper, only the nickel composition in weight percent will be given. The remainder of the alloy is always iron.

To discuss these observations it is necessary to consider the equation describing the resonance condition:

$$\left(\frac{\omega}{\gamma}\right)^2 = \left(H_0 + 4\pi M_s + \frac{3\lambda\sigma}{M_s} + H_k \cos^2\theta\right)(H_0 + H_k \cos 2\theta) \quad (1)$$

where ω is the angular microwave frequency, γ is the gyromagnetic ratio, λ and M_s are the saturation magnetostrictive constant and saturation magnetization respectively, θ is the angle between the applied dc field and the easy axis, σ is a radially isotropic stress, and H_k is the uniaxial anisotropy field. This equation is derived by usual methods (10,11) in which the effective demagnetizing factors are

$$N_x = -3\Delta\sigma/M_s^2 - 2K_u \sin^2\theta/M_s^2,\ N_y = 4\pi,$$

and

$$N_z = -3\Delta\sigma/M_s^2 - 2K_u \cos^2\theta/M_s^2,$$

where K_u is the uniaxial anisotropy constant equal to $M_s H_k/2$. Substituting these into Kittel's resonance condition (12),

$$(\omega/\gamma)^2 = [H_0 + M_s(N_y - N_z)]\,[H_0 + M_s(N_x - N_z)],$$

gives Eq. (1). We have used H_k rather than σ_u, a uniaxial anisotropic stress (13), since the uniaxial anisotropy in the field necessary to magnetize a film may have other origins as well. These include a short-range directional ordering of Fe atom pairs (14-17) in the case of the Permalloy films, a magnetoelastic effect (18,19), or an ordering of defects (20-22a) in the case of iron and nickel as well as the Permalloy films. Note also that Eq. (1) was derived assuming that the magnetization is uniform throughout the sample. It has been proposed (23) that multiline resonance patterns, for the case of parallel orientation of the dc field and the film plane, are due to a variation in magnetization throughout the film thickness. Uniformity in M_s will be assumed in the present work, since all films investigated had only one line, except for samples H-6 (five lines), K"-1 and K"-2 (four lines each), and O-1 and O-9 (two lines each). However, it is not entirely clear that the absence of a multiline spectrum indicates uniformity in M_s. For the films with more than one line, the most intense line occurred at the highest field, and this was the one investigated before and after irradiation.

To compare the experimental and theoretical angular dependence of the resonance field, $H_0(\theta)$, the experimental values for H_0 at $\theta = 0°$ and $\theta = 90°$ were substituted into Eq. (1); the two simultaneous equations obtained, which gave a cubic equation in $3\lambda\sigma/M_s$ were solved for $3\lambda\sigma/M_s$ and H_k. The magnetization was assumed to be unchanged by the irradiation. The calculated $H_0(\theta)$, obtained from Eq. (1) with the previously determined values of H_k and $3\lambda\sigma/M_s$, and the experimental $H_0(\theta)$ for film K"-2 are shown in Fig. 1 (before irradiation) and in Fig. 2 (after irradiation). The agreement between the observed and calculated curves is quite good before as well as after irradiation. The observed and calculated curves for films of other compositions and for films with a single resonance line gave similarly good agreement. This indicates that Eq. (1) describes the angular variation of the resonance field for thin films very well, whether or not the films have been irradiated.

If the change in H_0 resulting from irradiation is due entirely to an irradiation-induced change in M_s then M_s would have to increase by around 1/2, 2, and 4 percent for iron, nickel, and 83 percent Ni-Permalloy, respectively. Although it is unlikely that M_s would change for the pure metals, a change in M_s of 4 percent for the 83 percent Ni film is not inconceivable in view of the fact that ordering is possible for this composition as well as for the other Fe-Ni alloy films. For bulk samples around 75 percent Ni, M_s, could

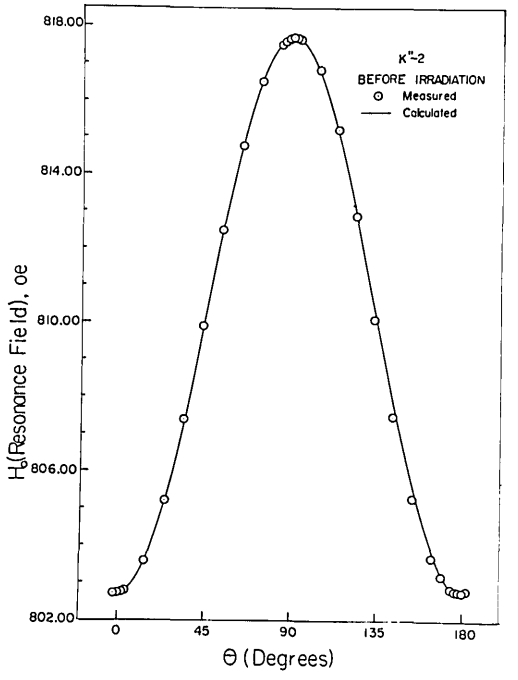

Fig. 1 - A comparison of the measured and the calculated angular dependence of the resonance field for Sample K"-2 before irradiation. The thickness and composition of K"-2 are the same as for K"-1.

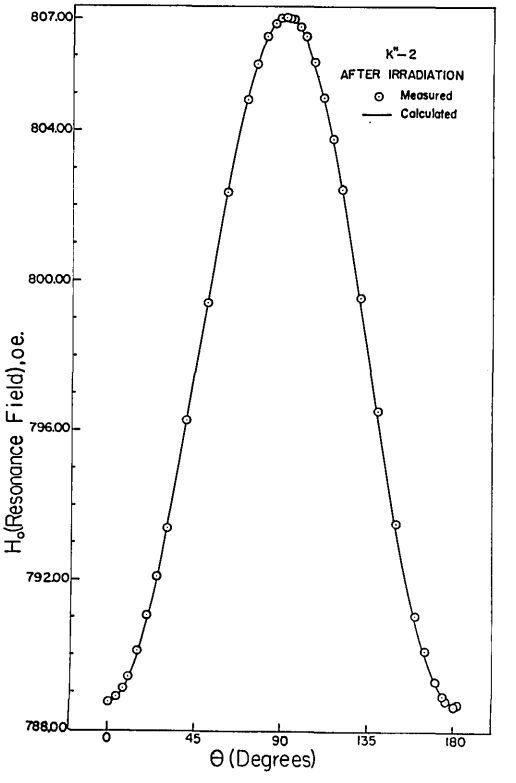

Fig. 2 - A comparison of the measured and calculated angular dependence of the resonance field for Sample K"-2 after irradiation.

change by 5 percent (24a,25)* as a result of ordering; however, neither the degree of order attained nor the dependence of M_s on ordering in thin films is known. Also, because of the lack of any measurements on the effects of irradiation on λ, it will be assumed that λ remains constant. Thus all changes can be attributed to changes in σ, M_s, and H_k for the alloy films.

FILM-STRESS CHANGES AND THE EFFECT OF THE SUBSTRATE

It is especially significant that both fused quartz (26) and soft glass (8b) contract under heavy neutron irradiation and, presumably, also under He^3 irradiation. Stress changes in the substrate resulting from the He^3 irradiation may be reflected as stress changes in the film, and if the film is already in tension, this contraction can result in a decrease in the stress of the film. Fused quartz exhibits a saturation density increase (27) of 2.7 percent at a neutron irradiation of 6×10^{19} fast neutrons/cm^2. It can be shown (8c,28a) that the ratio of displaced atoms in quartz caused by 6×10^{19} fast neutrons/cm^2 to that caused by 2.9×10^{17} He^3 particles/cm^2 is 0.66. Since 6×10^{19} neutrons/cm^2 changes the fused-quartz density to its saturation value, it is reasonable to assume that 3×10^{17} He^3 particles/cm^2 would have a similar effect.

In order to investigate the effect of damage in the substrate on the observed changes in the film, a set of films, prepared on three different substrates, was made. Since the films were all evaporated simultaneously, the variables (thickness, composition, substrate temperature) introduced by the evaporation were the same for all the films. Table 1 gives the results obtained for films S-1 (crystal quartz substrate), S-5 (soft glass), and S-9 (fused quartz). The difference in the observed values for H_e and H_h both before as well as after irradiation shows that there is a definite effect of the substrate on the results. Since the composition of these films is around 89 percent Ni, probably only little ordering takes place, and, in this case, we will assume that M_s does not change. The quantities $3\lambda\sigma/M_s$ and H_k were obtained as indicated previously from Eq. (1). The values of H_k, given in Table 1 and obtained by the exact solution of Eq. (1), differed by only 10 percent (for Ni) and 2 percent (for Fe) from those values of H_k obtained by the approximate expression $H_k \cong (H_h - H_e)/2$.

The saturation magnetization used to obtain $\Delta\sigma$, the change in the radially isotropic stress, and H_k from Eq. (1) for the films of a given composition was taken as that of the bulk material with the same composition. Therefore, it is important to note that although $3\lambda\sigma/M_s$, obtained by solving Eq. (1), depends significantly on the choice of M_s, the value of $\Delta(3\lambda\sigma/M_s)$ (the irradiation-produced change in $3\lambda\sigma/M_s$) as well as the value of H_k are independent of M_s. That is, the solution of Eq. (1) for $\Delta(3\lambda\sigma/M_s)$ at $\theta = 0$ degree is

$$\Delta\left(\frac{3\lambda\sigma}{M_s}\right) = \left[\frac{(\omega/\gamma)^2}{(H_e' + H_k')(H_e + H_k)} + 1\right] (H_e - H_e' + H_k - H_k') \qquad (2)$$

where the primed values refer to the values after irradiation. Also, by eliminating $3\lambda\sigma/M_s$ from Eq. (1) written for $\theta = 0$ degree and $\theta = 90$ degrees, we obtain H_k from the cubic equation,

$$H_k^3 + 2H_k^2(H_e - H_h) + H_k\left[(H_e - H_h)^2 - 2\left(\frac{\omega}{\gamma}\right)^2 - H_eH_h\right] + \left[\left(\frac{\omega}{\gamma}\right)^2 + H_eH_h\right](H_h - H_e) = 0 .$$

It is seen that neither of these equations involves M_s and that $\Delta\sigma$ depends on M_s only directly. Thus an error in the choice of the value for M_s does not affect H_k and affects $\Delta\sigma$ only directly.

*Nesbitt, et al. (25), observed an increase of 2 percent in the saturation magnetization of bulk single crystals of 76 Ni and 50 Ni and a decrease of a few percent for a 30 Ni crystal. This is a little surprising in view of the rather small neutron flux used - 5×10^{17} n/cm^2.

As Table 1 shows, $\Delta\sigma$ for the film on fused quartz (S-9) was greater than that for the film on the soft glass (S-5). These results are in accord with deductions of the stress changes to be expected from the known radiation-induced density increases in fused quartz, 3 percent, compared with plate glass, 1 percent (8b), which is presumably similar to soft glass.

Perhaps the most striking example of the effect of the substrate on the irradiation-induced changes of H_e and H_h is given by the behavior of the film S-1 on the crystal quartz substrate. The crystal quartz substrate was γ-quartz, with the surface plane being a (101) plane and with an AT cut as determined by x-ray diffraction.

If the known coefficients of thermal expansion for crystal quartz are "translated" into coefficients of the thermal expansion for a (101) plane of the quartz, the strains in two perpendicular directions on the substrate surface occurring as a result of a temperature change from 300°C (the evaporation temperature, in this case) to room temperature are 4.12×10^{-3} and 3.11×10^{-3} (28b). The strain induced in the film for the same temperature change is 3.46×10^{-3}. Thus, one might expect the film to be in tension along one axis and compression along the other, if the differential thermal expansion between the substrate and the film, alone, determines the stress in the film. But, in addition to the differential thermal expansion stresses, the film may have an intrinsic stress (29) which should be at least radially isotropic in the plane of the film, and perhaps completely isotropic throughout the film except near the surfaces. To check the possibility of the existence of orthogonal compressive and tensile stresses superposed on the intrinsic stress in the film, one can derive the resonance condition starting from the equation (10).

$$\left(\frac{\omega}{\gamma}\right)^2 = \left[H + 4\pi M_s + \frac{3\lambda}{M_s}(P_{33}-P_{22})\right]\left[H + \frac{3\lambda}{M_s}(P_{33} - P_{11})\right] \tag{3}$$

where H is the resonance field and P_{11}, P_{22}, P_{33}, are the diagonal components of the stress tensor for orthogonal axes in and perpendicular to the plane of the film.

Taking the principal stresses to lie along the x and z axes of the film, the stresses referred to arbitrary axes making an angle θ with respect to the x axis are given by (30)

$$P_{11} = \tau_1 \cos^2\theta + \tau_3 \sin^2\theta + \sigma$$

$$P_{22} = \sigma$$

$$P_{33} = \tau_1 \sin^2\theta + \tau_3 \cos^2\theta + \sigma$$

where a uniform three-dimensional component, σ, due to the intrinsic stress has been added to the components brought about by the orthogonal principal stresses τ_1 and τ_3. Equation (3) becomes

$$\left(\frac{\omega}{\gamma}\right)^2 = \left[H + 4\pi M_s + \frac{3\lambda}{M_s}(\tau_1 \sin^2\theta + \tau_3\cos^2\theta)\right]\left[H - \frac{3\lambda}{M_s}(\tau_1 - \tau_3)\cos 2\theta\right]. \tag{4}$$

At θ = 0 degree,

$$\left(\frac{\omega}{\gamma}\right)^2 = \left[H_0 + 4\pi M_s + \frac{3\lambda}{M_s}\tau_3\right]\left[H_0 + \frac{3\lambda}{M_s}(\tau_3 - \tau_1)\right]. \tag{5}$$

At θ = 90 degrees

$$\left(\frac{\omega}{\gamma}\right)^2 = \left[H_{90} + 4\pi M_s + \frac{3\lambda}{M_s}\tau_1\right]\left[H_{90} + \frac{3\lambda}{M_s}(\tau_1 - \tau_3)\right], \tag{6}$$

where H_0 and H_{90} are the resonance fields at θ = 0 degree and θ = 90 degrees, respectively. If τ_1 and τ_3 are of opposite signs, it can easily be shown that H_0 will be smaller (or larger) than H_{no}; also H_{90} will be larger (or smaller) than H_{no}, where H_{no} is

the resonance field calculated from Eq. (4), assuming that $\tau_1 = \tau_3 = 0$. From Eq. (4), we get $H_{no} = 1086$ oe. The observed resonance fields are $H_0 = 954.4$ oe and $H_{90} = 1101.5$ oe. Thus the principal stresses are, indeed, of opposite signs, and there is (either alone or superposed on an intrinsic stress) a contraction along one direction of the film and an expansion along a perpendicular direction. An approximate value for $\tau_3 - \tau_1$ can be obtained from Eqs. (5) and (6) by taking the first bracketed term on the right-hand side of both equations as being equal and dividing to get

$$\tau_3 - \tau_1 = \left(\frac{H_{90} - H_0}{2}\right)\left(\frac{M_s}{3\lambda}\right). \tag{7}$$

Using bulk values for M_s and λ and the experimental values for H_{90} and H_0, we get $\tau_3 - \tau_1 = -1.4 \times 10^9$ dyne/cm^2. The value calculated on the basis of thermal expansion gives $\tau_3 - \tau_1 = 1.6 \times 10^9$ dyne/cm^2. The agreement is quite good.

Even if the intrinsic stress were taken as a radially isotropic stress in the x-z plane, so that $P_{22} = 0$, the final approximate solution for $\tau_3 - \tau_1$ given in Eq. (7) still holds. There seems to be no a priori reason to believe that imperfections formed during the evaporation of the film produce a stress only in the plane of the film. Hence the above choice of an isotropic (hydrostatic) stress rather than a plane radial stress for the intrinsic stress appears to be the less restrictive viewpoint.

The effect of the substrate on the irradiation-induced changes in H_e and H_h for S-1 can be understood by comparing the data for samples S-1, S-5, and S-9. In the latter two cases, both H_e and H_h decreased; in the former H_e increased whereas H_h decreased (Table 1). The behavior of the latter two films can be related to an irradiation-produced contraction of the substrate, to an expansion of the film, or to both. For the film on the crystal quartz, the quantity $\tau_3 - \tau_1$ after irradiation is -0.6×10^9 dyne/cm^2, as calculated from Eq. (7). A comparison of this figure with $\tau_3 - \tau_1$ before irradiation (-1.4×10^9 dyne/cm^2) indicates that the substrate expanded anisotropically as a result of the irradiation. In addition, this analysis shows the large effect of the substrate on the irradiation-induced changes observed. The observation by others (31,32) of an anisotropic expansion of crystal quartz under neutron bombardment agrees qualitatively with the result obtained here for He^3-irradiation.

Films of two different compositions, 78 percent Ni (the V-set) and 36 percent Ni (the X-set), were evaporated onto soft glass and metallurgically polished copper. The resonance-field changes with irradiation of films of both compositions were of the same sign, independent of the substrate, as Table 1 shows. However, the magnitude of the changes appeared to be different for films of the same set, but on different substrates. It is also seen that the change in the anisotropy field $\Delta H_k = \Delta [(H_h - H_e)/2]$, was very nearly zero for the two films on the copper substrates. This result indicates that the change in the anisotropy field for films on copper substrates, as well as the change in stress (or perhaps in M_s), is affected by damage in the substrate.

It is clear from the above examples that the substrate plays a significant role in the changes observed in the resonance fields as a result of the He^3 irradiation. On the other hand, defects and resultant stress changes are also produced in the film, itself. In fact, the apparent decrease of the tension in the films could be brought about by a lattice expansion of the film as well as by a contraction of the substrate. However, for a radial stress change of -0.4×10^9 dyne/cm^2 for nickel (H"-5) and -4.8×10^9 dyne/cm for iron (N'-2), the change in the radial strain would have to be -1.7×10^{-4} for nickel and -2.3×10^{-3} for iron. These values seem rather large for irradiation-induced expansion in metals, especially for room-temperature irradiations. For example, deuteron-irradiation of copper at 77°K by McDonell and Kierstead (33,34) produced an expansion which was a factor of 19 below that calculated using the simple displacement theory (35); 10°K deuteron-irradiations of copper by others (36,37) yielded a lattice expansion near the theoretically expected amount–the observed fractional increase in copper was 3.8×10^{-4}.

If this number is compared with the strain calculated for the iron and nickel films, it would then seem reasonable to suspect that most of the stress change comes from the substrate and not from the film. Nevertheless, the differences in the observed values of $\Delta\sigma$ for iron (N'-2) and nickel (H" -5), both evaporated onto soft glass, imply that there are some irradiation-induced changes in σ as a result of changes in the films.

The large change in σ could also be the cause of the decrease in the coercive force, H_c, previously reported (4). Generally, one would expect an increase in the defect concentration to cause an increase, not a decrease, in H_c. A large relaxation of the stress in the film, however, could more than compensate the effect of the increased defect density and result in a reduction of H_c. Experiments designed to separate film effects from substrate effects by irradiating unsupported films are in progress.

MAGNETIC FIELD EFFECT

The magnetic state of the film during irradiation was found to be an important factor in determining the change in H_k and the rotation of the easy axis. A study of this effect was made on two sets of films; the individual films of one set were irradiated in either the demagnetized, remanent, or magnetically saturated state. Each set of films was evaporated simultaneously onto fused quartz substrates so that the changes observed depended only on the magnetic state during irradiation.

The results are given in Table 2, which also shows values of $\Delta\sigma$ calculated, assuming no changes in M_s. There appears to be only a very small dependence of $\Delta\sigma$ on the state of magnetization of the film during irradiation. Table 2 also shows that irradiating a film in the remanent state results in smaller H_k than is obtained by irradiating the film in a saturating magnetic field (425 oe in the film plane). The anisotropy field, H_k, is smaller still when the film is irradiated in the demagnetized state. This behavior can be explained qualitatively by assuming that H_k increases equally for each domain of a multidomain film in the direction that the magnetization vector, $\vec{M}$, is pointing during irradiation. The final value of the anisotropy field, H_k', averaged over the entire volume of all the domains will be larger, the larger are the number of domains which have an $\vec{M}$ pointing along a given direction. Since in a saturated film, $\vec{M}$ points along the direction of the applied field for nearly all of the film volume, the saturated film will show the largest H_k'. Films in the remanent and demagnetized states have smaller volumes in which $\vec{M}$ is pointing along a given direction and, hence, will show correspondingly smaller H_k''s.

The application of a magnetic field at an angle of 45 ± 10 degrees to the easy axis and in the plane of the films during irradiation produced the following results. After irradiation, the easy-axis direction was in the direction of the magnetic field maintained during the irradiation. This result occurred not only for samples Q-7 and O-1 (as well as films of all compositions–see Table 3), which were irradiated in the presence of an applied field only once, but also for samples Q-9 and O-9, which were irradiated twice–first with no applied field and then with an applied field (Table 2). Thus, it does not seem to be important whether or not the sample had been previously affected by radiation, even if it were irradiated to the point of saturation.* The rotation of the axis must therefore be a purely unsaturable effect, at least insofar as the amount of flux received by the samples to date (i.e., $\simeq 5.8 \times 10^{17}$ He^3 particles/cm^2 for sample O-9) is concerned.

Increases in H_k may be related to irradiation-induced short-range directional ordering of iron atom pairs or of defects. These effects probably also govern the easy-axis rotation by the irradiation. However, in pure Fe and pure nickel films, it is impossible

*That 3×10^{17} He^3/cm^2 almost saturates the sample can be seen from the results of Q-9 in Table 1. The changes in H_e and H_h after the second irradiation were quite small compared to their changes after the first irradiation.

Table 2
Magnetic Field Effect

Sample	Composition (percent)	Magnetic State During Irrad.	Before H_k (oe)	After H_k (oe)	$\Delta\sigma$ (10^9 dyne/cm^2)	Easy Axis Rotated?
Q-8	85 Ni	Demagnetized	2.2	3.7	-10.6	
Q-6	85 Ni	Remanent	1.8	5.1	-10.8	
Q-9	85 Ni	Remanent	2.6	5.1	-10.9	
Q-9*	85 Ni	425 oe†				Yes
Q-7	85 Ni	425 oe†	2.4	6.1	-11.4	Yes
O-9*	100 Fe	425 oe†				Yes
O-1	100 Fe	425 oe†				Yes

*Samples Q-9 and O-9 were irradiated twice–first in the remanent state and then in the magnetically saturated state.

†Field applied at 45 degrees to the easy axis.

to explain the rotation of the easy axis on the basis of short-range directional ordering of Fe atom pairs. Here, the explanation must be based on an alignment, during irradiation, of either those defects produced by the irradiation or of defects or impurities present in the sample before irradiation. In a demagnetized, multidomain film, $\vec{M}$ for a given domain points along one of the easy axes of that domain. The easy axis may be a crystalline easy axis or a uniaxial easy axis produced by an alignment of impurities or imperfections (20,21,22a). By means of an applied field, $\vec{M}$ for a domain can be made to point in a direction other than an easy axis. Since enhanced diffusion of atoms takes place during irradiation (38), we propose that the direction of the defect alignment rotates into the direction of the field applied during irradiation, and hence the easy axis of the region rotates toward the direction that $\vec{M}$ has during irradiation. If the film is magnetically saturated (approximately a single-domain film) during irradiation, this realignment of defects takes place such that the direction of the easy axis for all regions of the film will be rotated toward the direction of $\vec{M}$.

If a magnetic field with a value smaller than that needed to saturate the film is applied during irradiation, the film will now consist of a number of domains. In some of these domains the direction of $\vec{M}$ for a given domain ($\vec{M}_{local}$) lies along the easy axis of the film; in others, the direction of $\vec{M}_{local}$ is not along the film easy axis. Hence for the domains in which the direction of $\vec{M}_{local}$ lies along the easy axis, there is no rotation of the easy axis during irradiation; but in those domains in which $\vec{M}_{local}$ does not lie along the film easy axis during irradiation, there is a rotation of the easy-axis direction toward the direction of $\vec{M}_{local}$ (or $\vec{H}_{applied}$, the applied field during irradiation) for these domains. The amount of rotation will depend on the amount of alignment of defects which, in turn, depends on the amount of irradiation. That is, for complete rotation of the easy axis in a given region there should be sufficient diffusion to result in complete defect realignment. Thus there are two factors which govern the rotation of the easy axis during irradiation of the film in an applied field: (a) the magnitude of the applied field, and (b) the integrated irradiation flux.

The underlying basis of this proposed mechanism is that, in unirradiated pure metal films, the cause of the uniaxial anisotropy is an alignment of defects in the film during evaporation. It would be interesting to determine theoretically if the energy of the film is changed by having vacancies or interstitials lined up either in the direction of, or at 90 degrees to, the applied field.

Previous observations have been made of the rotation of the easy axis either as a result of annealing (39,40) or as a result of irradiation (4). The above ideas may help to explain the data (4) in which 72 Ni thin films were irradiated with neutrons and He^3 particles in a saturating field applied along the hard axis. The observed rotation was not 90 degrees, but 64 and 78 degrees for the neutron and He^3 irradiations, respectively. The density of displacements may have been too low to rotate the axis completely into the direction of $\vec{H}_{applied}$. In addition, according to the above two criteria, the neutron-irradiated film should show a smaller amount of rotation than the He^3-irradiated film, since 3×10^{17} neutrons/cm^2 should produce fewer displacements and consequently less diffusion than 9×10^{16} He^3 particles/cm^2. This idea is in agreement with the larger rotation observed for the He^3 -irradiated film.

In the case of the Permalloy films which had their easy axes rotated, short-range directional ordering of Fe atom pairs may play a role as well as alignment of defects. This phenomenon is illustrated by another effect observed previously following neutron irradiation[4] –namely, the reduction in the uniaxial anistropy constant K_u, of the same sample that had its easy axis rotated only 64 degrees. A similar effect was observed in annealing experiments of unirradiated films (40). These results can be explained on the basis of short-range directional ordering of Fe-Fe atom pairs as well as by alignment of defects. For a Permalloy film, the realignment of Fe-Fe pairs occurs in the direction of the field applied at some angle to the easy axis during annealing or irradiation. This realignment reduces H_k as long as it is not complete and the easy axis does not rotate at all or does not rotate completely. In addition to the realignment of Fe-Fe pairs during irradiation, the alignment of defects created by the irradiation will tend to increase H_k. Thus as irradiation proceeds (with a field applied at some direction other than the easy axis), H_k decreases at first due to partial realignment of Fe-Fe pairs and then increases as the alignment of defects and more complete realignment of Fe-Fe pairs occurs.

The above mechanism is somewhat similar to that proposed by Pugh (22b) to explain the annealing data and reduction in K_u observed by Segmüller (41). The separation of the effect of alignment of defects and alignment of atom pairs cannot be made at the present time for the Permalloy samples investigated in the present work.

EFFECT OF COMPOSITION

After the results discussed above were obtained, a series of films of various compositions of Fe and Ni were evaporated under the same conditions. That is, the substrate cleaning, evaporation procedure, and annealing after evaporation were all the same for each set of films. In addition, all eight films (Table 3) were irradiated at one time with a magnetic field of 168 oe applied in the plane of the film and at 45 degrees to their original easy axes. The use of the magnetic field ensured that the magnetic state of all samples during irradiation was the same and allowed a study of the rotation of the easy axis to be made over the entire composition range.

Since the films are all on similar substrates, the variation of the changes δH_e and δH_h with composition was due entirely to irradiation-produced processes in the films. No quantitative account can be given for the variation at the present time, but it seems clear that around 82 Ni, there is a minimum in δH_e and δH_h. This minimum may be a result of larger increases in M_s for films as the composition corresponding to zero magneto-crystalline anisotropy is approached. The values of δH_e and δH_h for the 76 Ni film are out of line when compared with the remaining data. The comparatively small changes in H_e and H_h found for the 76 Ni film may be attributed to the following three effects.

Table 3
Dependence of Resonance Field Changes and Half-Width Changes on Composition

Sample	Composition (percent)	Thickness Å	Irradiation	H_e (oe)	H_h (oe)	δH_e (oe)	δH_h (oe)	$*H_k$ (oe)	Initial ΔH (oe)	$\delta(\Delta H)$ (oe)	Easy axis rotated?
H″-5	100 Ni	6300	Before	1386.5	1389.5			1.5	420		
			After	1371.2	1379.9	-15.3	-9.6	4.3		-39	Yes
G″-5	91.5 Ni	9400	Before	1119	1125				218		
			After	1101	1109	-18	-16	4.3		-23	Yes
S-1	89 Ni	3000	See Table 1						81.8	-1	
S-5	89 Ni	3000							82.8	-3	
S-9	89 Ni	3000							79.0	-4	
F″-4	84.5 Ni	4600	Before	986.9	987.3			0.2	77.2		
			After	955.1	966.8	-31.8	-20.5	5.9		-4.5	Yes
I″-6	82 Ni	7100	Before	946.7	949.2			1.3	83.9		
			After	911.3	924.2	-35.4	-25.0	6.5		-5.9	Yes
K″-1	76 Ni	1800	Before	804.4	816.9			6.2	34.1		
			After	791.1	808.8	-13.3	-8.1	8.8		+0.2 ≅ 0	Yes
E″-6	69 Ni	5700	Before	765.9	772.9			3.5	62.8		
			After	732.8	763.8	-33.1	-9.1	15.5		-5.1	Yes
L″-7	53 Ni	3300	Before	648.7	663.1			7.2	53.8		
			After	629.2	670.9	-19.5	+7.8	20.9		-4.7	Yes
A″-7	26 Ni	4800	Before	476.7	501.6			12.4	222		
			After	479.3	506.2	+2.6	+4.6	13.5		-15	Yes
N′-2	100 Fe	540	See Table 1						110	-2	

Note – All films of the double prime sets were evaporated onto polished soft glass substrates at 250°C under identical conditions. N′-2 was evaporated onto soft glass at 300°C.
Films of the S-set were evaporated onto various substrates (see Table 1) at 300°C.

$*H_k$ is obtained from $(H_h - H_e)/2$.

δH_e and δH_h are the changes in H_e and H_h; initial ΔH is the initial half-width; $\delta(\Delta H)$ is the change in the half-width.

1. Substantially more long-range order may occur in the 76 Ni film, and hence M_s may be changed differently for this composition.

2. The 76 Ni film exhibited four resonance lines, of which the data for the most intense line is given in Table 3. Since the multiline pattern was not seen for the other films, the cause of the multiline pattern may also be responsible for the unusual behavior of H_e and H_h for the 76 Ni film.

3. The thickness of this film was much less than the thickness of the other films. If thickness is a contributing factor, the data suggest that there is a critical thickness below which defects easily reach the surface, leaving the film less heavily damaged than films of greater thickness.

For the films between 26 and 53 Ni, the resonance fields increased following irradiation. Films of 34 and 37 Ni also showed increases in both H_e and H_h (Table 1). For the film with the higher nickel concentration (53 Ni), only H_h increased, whereas for a 50 Ni film, also given in Table 1, H_e decreased, but there was little change in H_h. The difference between the two cases may be caused by the difference in temperature of irradiation (≃ 80°C for L″-7 and 190°C for H′-1).

The effect of composition on H_k obtained after irradiation for the films listed in Table 3 is shown in Fig. 3. Since H_k is a measure of an anisotropic effect, and since the effect of the substrate on the film should be isotropic, the results obtained for H_k are connected with radiation damage in the film alone. (See, however, the preceding discussion

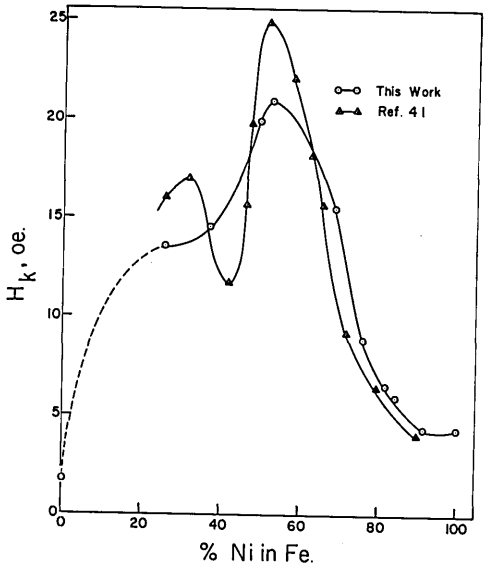

Fig. 3 - Compositional dependence of the uniaxial anisotropy field, H_k, after irradiation.

of films on copper substrates.) The anisotropy field, H_k as a function of composition shows a variation similar to that obtained by dc torque-magnetometer techniques. Previously published data (42) of K_u was converted to H_k and is also plotted in Fig. 3. The qualitative agreement between the two sets of data is good. The quantitative differences may be due to the inaccuracies in the determination of the compositions or of the values of M_s, as well as to slight differences in film preparation. It is interesting to observe that the two techniques of measuring H_k on two different sets of films give such close agreement.

The final H_k values achieved by the two films (H'-1 and L"-7) near 51 Ni are almost the same in spite of the difference in irradiation temperature. This suggests that irradiation is a more important factor than temperature in governing the final arrangement of the defects for these films.

HALF-WIDTHS

The half-width, ΔH, of the resonance line and the half-width change, $\delta(\Delta H)$ due to the irradiation for films of various compositions is given in Table 3 and shows two main features.

1. Half-width change $\delta(\Delta H)$ is large and negative for the pure nickel film (negative magnetostriction) and goes through 0 around the 76 Ni composition. The term $\delta(\Delta H)$ again becomes negative for films on the low-nickel side of the 76 Ni composition.

2. There appears to be some small dependence of $\delta(\Delta H)$ on the substrate, as shown by the data for films of one set, S-1, S-5, and S-9, evaporated onto substrates of three different types.

The large half-width changes may be a result of the stress changes due to the substrate contraction. This suggestion is partly justified by noting that Biller (2) observed that the linear change in the half-width of polycrystalline bulk nickel samples with applied tension was 11 oe/kg/mm^2. To translate this directly to the type of stress change we have in, say, the nickel film would yield a half-width change of about -45 oe. The observed change was -39 oe. Good agreement between the two values is somewhat surprising in view of the fact that commercial nickel was used for the bulk experiments and high-purity nickel was used in the present experiments.

Biller also found that the half-width changes of Mumetal and nickel, before and after the material was highly plastically deformed by scratching the surface, were different and attributed this behavior to the magnitude and sign of the magnetostrictive constant. The half-width change observed here appears to go to zero for compositions around 76 Ni rather than 82 Ni. This result implies that for these films, the half-width change may be related to the magnetocrystalline anisotropy constant, which also goes through zero at 76 Ni (24b). However, for films of other sets, not evaporated under conditions as identical as those for films listed in Table 2, $\delta(\Delta H)$ was zero around 85 Ni.

The present work still does not indicate whether radiation-induced defects in the film itself change the half-width. One might expect that the defects would act as scattering centers for spin waves in the film. This would decrease the relaxation time and hence increase the half-width for all compositions. If this effect occurred, it may have been masked by the change in ΔH due to stress changes in the film. Additional studies on unsupported films are clearly called for, and these are being undertaken at the present time.

SUMMARY

The following results have been obtained by observing the resonance field H_0 and the half-width ΔH of the resonance line before and after He^3 irradiation.

1. The angular dependence of the measured values of the resonance field, $H_0(\theta)$, for a 76 Ni-Permalloy film agreed quite well with $H_0(\theta)$ calculated from the usual resonance equation.

2. In general, H_0 decreased with irradiation, with the decrease being around 2, 35, and 15 oe for the iron, 82 Ni-Permalloy, and nickel films, respectively.

3. The H_0 field increased for films with compositions between 26 and 37 Ni.

4. Changes in H_0 were different for films of a given set evaporated on different substrates.

5. By irradiating films in the demagnetized, the remanent, and the magnetically saturated states, it was found that the final value of H_k was larger, the larger the magnetic induction of the film during irradiation.

6. Irradiating films of all compositions in a magnetic field which lay in the plane of the film and at an angle of 45 degrees to the easy axis of the film rotated the easy axis into the direction of the field. This observation was the case for films whether or not they had received any previous irradiation.

7. The magnitude of the change in H_0 as a function of composition has a maximum near 82 Ni.

8. The variation of the values of H_k after irradiation with composition as measured by resonance techniques agrees qualitatively with observations made by other means.

9. The half-width changes due to irradiation vary with composition and become zero near 76 Ni.

The above results were interpreted on the basis of changes in the uniform radial stress and in the uniaxial anisotropy field in the film (for both the pure and the alloy films) and in M_s (for the alloy films). The fact that films on different substrates gave different results indicates that the substrate influences the changes observed and suggests

future experiments which would involve irradiating unsupported films. In addition, the effect of the easy-axis rotation brought about by the application of a magnetic field during irradiation suggests that for the pure Fe and pure Ni films there is a realignment of defects and for the alloy films, there is a directional short-range ordering of Fe-Fe pairs of atoms, or a combination of these two processes.

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13. ABSTRACT

Ferromagnetic-resonance measurements of 9.5 GHz were made on a number of films of pure iron and pure nickel, and alloys of iron and nickel (Permalloy) before and after 2-MeV He^3-particle irradiation. The film thicknesses varied from several hundred to several thousand angstroms. The He^3-particle flux was about $3\times10^{17}/cm^2$ and, during irradiation, the film temperature did not exceed 81°C, as determined by thin-film thermocouples. The resonance field as a function of angle in the film plane, $H_0(\theta)$, and the half-width, ΔH, were measured at room temperature. In general, H_0 decreased (by about 2 oe, 35 oe, and 15 oe for the iron, Permalloy, and nickel films, respectively) as a result of the irradiation, except for the composition range between 26 and 37 percent Ni, where H_0 increased. Also, the half-width generally decreased with irradiation, and the half-width change was smallest for compositions around 76 percent Ni. For the pure iron and nickel films, the changes in H_0 can be attributed to changes in the radially isotropic stress in the plane of the film, $\Delta\sigma$, and in the uniaxial anisotropic field, ΔH_k, assuming that the saturation magnetostrictive constant, λ, and magnetization, M_s, do not change with irradiation. For the alloy films where irradiation-produced ordering may occur, M_s, as well as σ and H_k, may also change. The changes in H_0 were different for films of a given set evaporated onto various substrates (soft glass, fused quartz, single-crystal quartz, and copper). Irradiating films in a saturating magnetic field, in the remanent state and in the demagnetized

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Metal films						
Resonance						
Uniaxial anisotropy						
Irradiation						
Ferromagnetic materials						
Iron						
Nickel						
Iron and nickel alloys						
Permalloy						

Abstract continued –

state gave H_k's which were larger, the larger the magnetic induction of the film during irradiation. Irradiating a film (or reirradiating a previously irradiated film) in a magnetic field also rotated the easy axis of the film into the direction of the field applied during irradiation. The rotation of the easy axis was observed over the entire composition range from pure iron to pure nickel. For the pure iron and pure nickel films, the rotation can be explained only on the basis of alignment of defects in the film during irradiation. For the Permalloy films, a short-range directional ordering effect might also apply. The variation with composition of the values of H_k after irradiation agree qualitatively with the values obtained by others using static techniques.